Main Sequence Fitting and the Hipparcos Open Cluster Distance Scale

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Abstract. The difference between the Hipparcos open cluster distance scale and that obtained from main sequence fitting is examined. The two color main sequence fitting technique of Pinsonneault et al. (1998) is extended to NGC 2516, NGC 6475, and NGC 6633. The error sources for main sequence fitting are examined, and possible evidence for systematic errors in the Hipparcos parallaxes is discussed.

1. Introduction

One of the most difficult and important issues in astronomy is the determination of distance scales. Until recently the open cluster distance scale was not generally regarded as controversial; however, this changed when the Hipparcos mission permitted the measurement of trigonometric parallaxes for a number of stars in open clusters more distant than the Hyades. The distances obtained from Hipparcos parallaxes are in significant disagreement with previous distance measurements obtained from main sequence fitting techniques in some of the best-studied systems in the sky (for example, the Pleiades and Praesepe clusters). This is not a problem with an easy answer; the technique of main sequence fitting is based upon a firm foundation in the theory of stellar structure and evolution and is supported by a wealth of empirical tests and constraints. On the other hand, the Hipparcos mission has provided an unprecedented database of fundamental distance measurements and there is a large body of solid astrometric work behind the Hipparcos measurements.

In this talk I will begin by summarizing the major issues involved, and follow with a brief description of main sequence fitting and the Hipparcos open cluster distance scales. I will then discuss the possible error sources in the main sequence fitting techniques and the possibility of systematic errors in the Hipparcos open cluster distances. Finally, I will close with an illustration of some of the other possible applications of main sequence fitting: namely, an age diagnostic for young clusters and the ability to assign more precise relative distances and metal abundances to less well-studied open clusters.

1.1. Why Does it Matter?

The differences between the Hipparcos and main sequence fitting distance scales might seem to be an arcane issue; however, it indicates that we are faced with one of three interesting possibilities:

- The systematic or random errors in main sequence fitting distances could be significantly larger than estimated. This could arise from underlying difficulties in the technique itself. Alternately the basic data, in particular the abundances of some of the best studied stellar systems, would have to be in serious error.
- The predictions of theoretical stellar models could be lacking some important ingredient, for example the change in stellar luminosity with age or abundance.
- The systematic errors in Hipparcos parallaxes could be underestimated.

All three classes of solutions have important implications. For example, variations in the helium abundance from cluster to cluster at fixed metal abundance could produce large changes in the distances inferred from main sequence fitting (see for example Belikov et al. 1998). If this is the explanation, however, large helium abundance variations from cluster to cluster would imply an unusual chemical evolution pattern and limit our ability to infer distances to individual stars even when their spectral type and metal abundance are known, possibly to the 0.3 mag level or worse. The problem is similar, although less severe, if the problem is in the relative metal abundances of different systems. If there are larger systematic errors than claimed for the Hipparcos parallaxes, that could affect some of the applications of the Hipparcos data.

In our view this requires a critical analysis of all methods, including the possibility of systematic errors in the Hipparcos parallaxes. We will begin with the technique of main sequence fitting itself, and follow with the Hipparcos open cluster parallaxes.

1.2. Open Cluster Distances Based on MS Fitting

There are two principal techniques for deriving the distances to open clusters by main sequence fitting: relative distances to the Hyades corrected for reddening, composition, and age; and absolute distances relative to theoretical calculations calibrated on the Sun and nearby stars with known parallax. Both have their advantages and disadvantages.

If the Hyades distance is regarded as known based upon direct distance measurement techniques, the relative distance of other clusters can be calculated with high precision, typically 0.02 mag or better (e.g., Johnson & Knuckles 1955; Pinsonneault et al. 1998) if the reddening of the other cluster is known. One can also compute cluster distances relative to theoretical isochrones. Isochrones are typically calibrated to reproduce the solar luminosity and radius at the age of the Sun, and can therefore in some sense be regarded as anchored on the Sun rather than the Hyades cluster. Theoretical models predict luminosity and effective temperature, while observers measure V magnitude and color; bolometric corrections and color-temperature relationships are therefore required to compute isochrones in the observational plane.

Age will affect the apparent distance of a cluster. In systems younger than about 100 Myr the lower main sequence stars are still contracting to the main sequence, while upper main sequence stars will be evolving off the main sequence. As a result, solar analogs are typically used to measure relative distances (short

pre-MS contraction times and long main sequence lifetimes make the corrections due to cluster age small and theoretically well-understood). Age is therefore usually not a major uncertainty in measuring the distance to a cluster.

Composition, however, will have a strong influence on the apparent distance of a cluster. In both theoretical models and direct parallax measurements, high metallicity stars appear brighter at fixed color than low metallicity stars. This is partially a stellar interiors effect; increased metal abundance makes stars of fixed mass slightly fainter and significantly cooler, moving them above the MS locus of lower abundance stars. Increased line blanketing in more metal-rich stars also makes them appear redder at fixed effective temperature. As a result, the apparent distance to an open cluster must be corrected for both reddening and the metal abundance. Changes in the helium abundance will move models in the theoretical plane, in the sense that a high helium abundance will make stars appear systematically fainter at fixed effective temperature or color; however, the spectral energy distribution and color-temperature relationship is insensitive to the helium abundance.

The principal virtue of measuring distances relative to the Hyades is that it relies on the slope of M_V with respect to [Fe/H]; different empirical and theoretical calculations of color-effective temperature relationships and bolometric corrections can disagree in their zero-point but are typically in reasonable agreement on the slope. Distances relative to the Hyades are, however, subject to zero-point shifts based on both changes in the adopted distance to the Hyades cluster and to the metal and helium abundance of the Hyades itself.

It is important to note that the above process of main sequence fitting is strongly based on empirical data from fundamental temperatures, the Sun, and theoretical models which agree with helioseismic data to a precision of order 0.1% (Basu et al. 1999).

In summary, the main error sources for main sequence fitting are the conversion from the theoretical to the observational plane, the reddening of the cluster, and the metal and helium abundances of the cluster.

1.3. The Hipparcos Open Cluster Distance Scale

The high precision and large number of stars in the Hipparcos catalog made it possible for the first time to derive parallaxes for enough stars in open clusters to provide trigonometric distances to systems other than the Hyades, as well as an extremely precise distance to the Hyades cluster itself ($m - M = 3.34 \pm 0.01$, Perryman et al. 1998). See, for example, Perryman et al. (1998) and van Leeuwen (these proceedings) for a discussion of the Hipparcos parallaxes to open clusters.

The major area of concern for the Hipparcos parallax distances to open clusters is the possibility of correlated errors on small angular scales. The typical density of stars in open clusters is significantly higher than the average across the sky; this is a known issue (e.g., Lindegren 1988; Narayanan & Gould 1999b and references therein) and the members of the Hipparcos mission attempted to correct for this potential error source. To explain the discrepancy between the main sequence fitting distances and the Hipparcos distances systematic errors of order 1 mas would be required, about ten times higher than the Hipparcos estimates of the global systematic errors.

2. The Problem

For this talk we have adopted an extension of the two-color main sequence fitting technique described in detail in Pinsonneault et al. (1998). Briefly, theoretical isochrones for stars bluer than a $B-V$ color of 0.75 were transformed to the observational plane using the Yale color calibration in two colors, $B-V$ and $V-I$ (Cousins). We used the well-defined main sequence of the Pleiades to construct an empirical isochrone for cooler stars, requiring that the distance obtained from successive cooler bins in the Pleiades be the same as the distance obtained for the hot stars in the Pleiades for each color. We applied differential corrections for the cluster age for systems with ages different from the Pleiades. After correcting for reddening, distances for individual stars were computed relative to a solar abundance isochrone and binned. The median distance of stars within 0.2 mag of the peak in the distribution of distances was used to determine the distance in each of two colors, $B-V$ and $V-I$.

Distances measured in $B-V$ and $V-I$ have different sensitivities to the metal abundance; a difference between the two relative to a solar abundance isochrones is therefore an indication of a cluster metal abundance different from the solar value. The difference in the $B-V$ and $V-I$ based distances was then used to estimate a photometric metal abundance and correct the distance, adopting the sensitivity of the color to changes in metal abundance from Pinsonneault et al. (1998). Figure 1 shows the results for the open cluster NGC 2516; relative to a solar abundance isochrone the two colors yield distinctly different distances. This indicates a distinctly subsolar metallicity; we derive [Fe/H] $= -0.26$.

The results from Pinsonneault et al. (1998) and more recent work reported here (Pinsonneault et al. 2000) are compared with Hipparcos distances from van Leeuwen (1999) and Robichon et al. (1999) in Table 1.

Table 1. Open Cluster Distances

Cluster	Age(Myr)	[Fe/H]	MSfit $m-M$	R99 $m-M$	vL99 $m-M$
α Per	60	+0.04	6.28 ±0.06	6.40 ±0.08	6.31 ±0.08
Pleiades	100	+0.01	5.62 ±0.05	5.36 ±0.07	5.37 ±0.07
NGC 2516	140	−0.26	7.77 ±0.10	7.70 ±0.16	···
NGC 6475	220	−0.13	6.99 ±0.10	7.24 ±0.19	7.15 ±0.19
Coma Ber	500	−0.07	4.54 ±0.05	4.70 ±0.04	4.77 ±0.05
Hyades	600	+0.13	3.34 ±0.04	3.33 ±0.01	···
Praesepe	600	+0.04	6.16 ±0.05	6.28 ±0.13	6.37 ±0.15
NGC 6633	700	+0.01	7.94 ±0.10	7.84 ±0.56	···

Note: R99 = Robichon et al. (1999). vL99 = van Leeuwen (1999).

Note that the Hyades distance is from Perryman et al. (1998). We have adopted photometric metal abundances for α Per, the Pleiades, NGC 2516, NGC 6475, and NGC 6633 based upon the refined main sequence fitting technique described in Pinsonneault et al. (2000); for the other clusters we have adopted the high-resolution spectroscopic abundances of Boesgaard & Friel (1992) and the distances computed in Pinsonneault et al. (1998). If the photometric [Fe/H] of +0.13 for Praesepe in Pinsonneault et al. (1998) was adopted in preference to the high-resolution spectroscopic abundance of +0.04 from Boesgaard & Friel

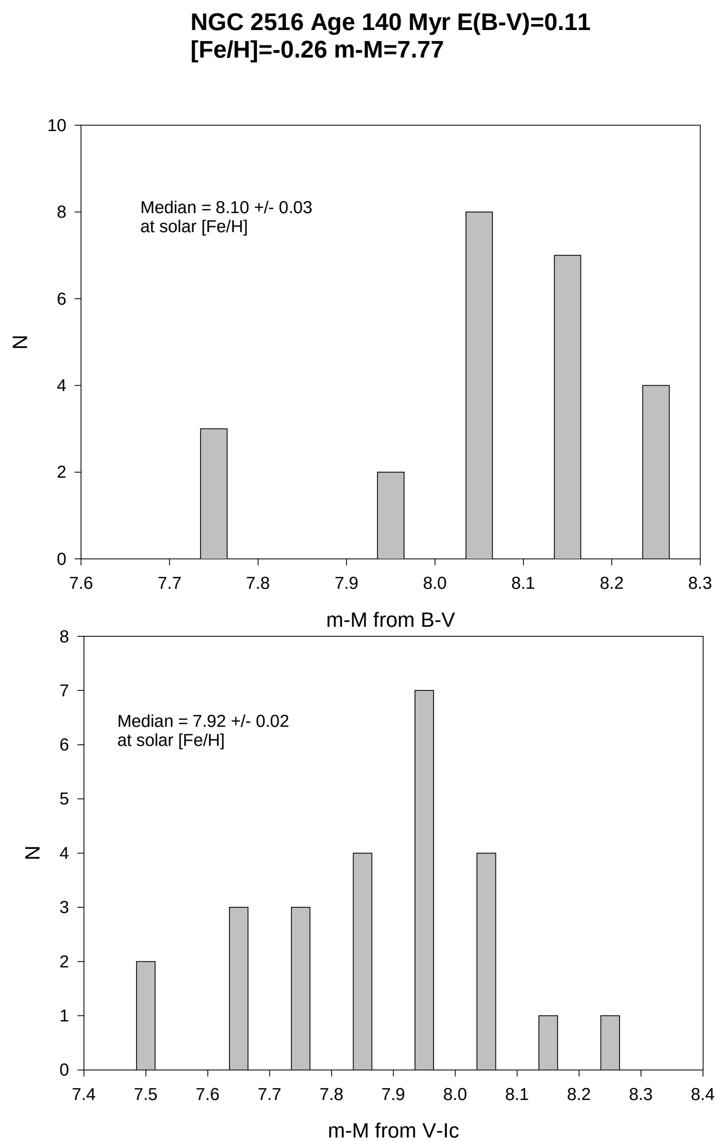

Figure 1. Example of the distance and metallicity determination using main sequence fitting in NGC 2516. That the metallicity of this cluster is subsolar is indicated by the derivation of a larger distance in $B-V$ than in $V-I$ (lower metallicity brightens the theoretical main sequence more in $B-V$).

(1992) the distance to Praesepe would rise to 6.25, close to the shorter Hipparcos distance. There are some systems (the Pleiades and Coma Ber) with formally large discrepancies; there are others (NGC 6475 and α Per) which may possibly be in conflict. There is no obvious pattern to the deviations with age or metal abundance, and furthermore the differences are not consistent with a simple scale shift to systematically shorter or longer distances. The Pleiades discrepancy is the most striking, and as a result it has been studied in the most detail.

3. Error Sources for Main Sequence Fitting

In our view none of the error sources for main sequence fitting are large enough to account for the differences in Table 1 above. As discussed in previous work, neither the reddening nor systematic differences between different sets of photometry are sufficiently large to change the results for well-studied systems such as the Pleiades. We do note, however, that this may not be the case for more distant and poorly studied systems. Four specific areas have been raised that could affect main sequence distances: age effects, helium abundance variations, metal abundance differences that are larger than inferred from main sequence fitting, and errors in the transformation between the theoretical and observational plane. We briefly discuss the major objections to these explanations below.

3.1. Age Effects

van Leeuwen (1999) raised the possibility that there was a trend in the discrepancy related to the age of the open clusters; this could be an indication that the changes in stellar luminosity as a function of age are not correctly predicted from stellar interiors models. However, we note that differences in stellar metal abundance need to be accounted for before comparing systems with different age. Thus the Hyades appears overluminous relative to other systems, but this is predicted from main sequence fitting because it is metal-rich. Figure 2 illustrates the difference between the present main sequence fitting distances and those of Robichon et al. (1999) once the metal abundances are taken into account; there are, for example, young systems with main sequence fitting distances that are both closer and further away than the Hipparcos distances.

3.2. Helium Abundance

Variations in helium abundance could explain the differences in Table 1 while remaining consistent with the observed metal abundances. However, there are two principal difficulties with this solution. The first is that it implies an extremely unusual chemical evolution pattern; the second is related to the relatively tight main sequence observed for nearby field stars with high-precision parallaxes (Soderblom et al. 1998). If there was a significant population of helium-rich solar abundance stars it would appear as a set of solar abundance subdwarfs in the nearby field. Soderblom et al. (1998) found no evidence for solar abundance subdwarfs in a kinematically selected sample of stars with precise Hipparcos parallaxes. This possibility can, and should be, tested directly in those open clusters with members hot enough to make measurement of the surface helium abundance possible. However, the absence of direct evidence of high helium

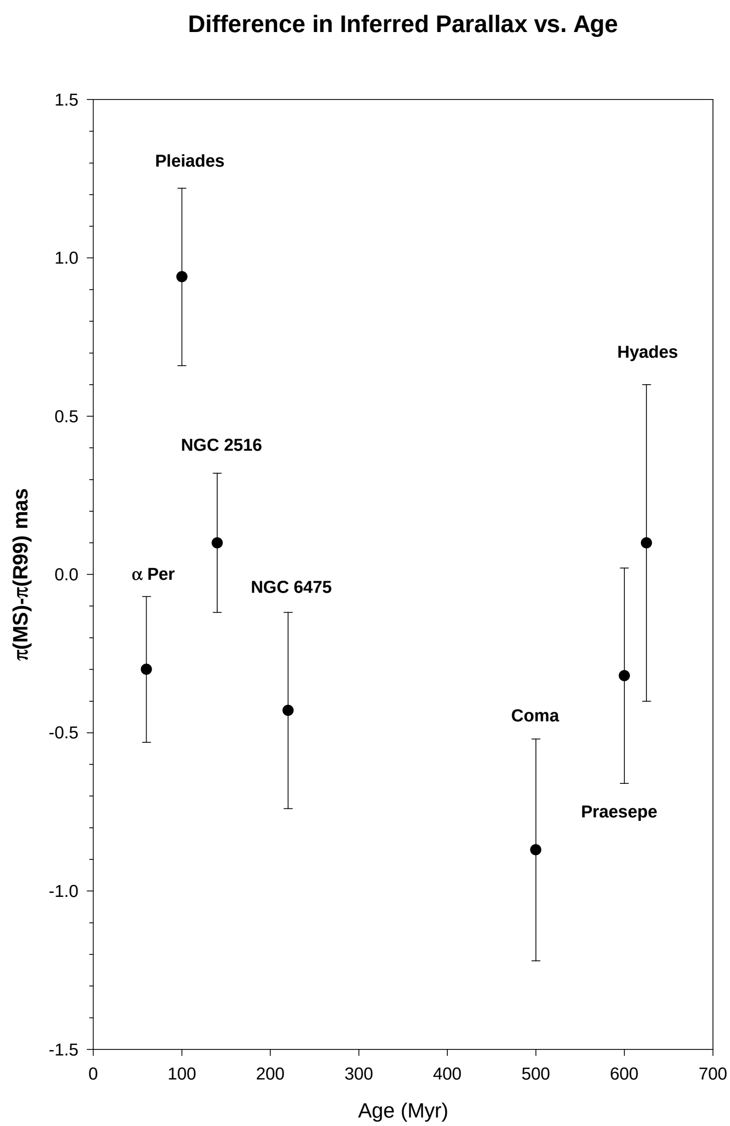

Figure 2. Difference between the main sequence fitting distances (MS) and Hipparcos distances (R99) as a function of cluster age. The distances have been expressed as a parallax in milliarcsec.

abundances or of field star analogues with accurate parallaxes makes this hypothesis an unlikely solution.

3.3. Metal Abundance

A change in the open cluster metal abundances is one possible means of explaining the discrepancy between the main sequence fitting and Hipparcos distances. For a number of more distant and less well-studied open clusters high-resolution abundances are absent or few in number and there is frequently only BV photometry available. Praesepe may be a case where the apparent discrepancy between the Hipparcos and main sequence fitting distance can be traced to its metal abundance, which can be inferred from both the photometry and high-resolution spectroscopic studies. However, there are several reasons why it will be difficult to reconcile the relative metal abundances of other well-studied systems with the values implied by the Hipparcos distances.

First, our photometric abundance scale is consistent with the high-resolution spectroscopic abundance scale of Boesgaard & Friel (1992). Relative abundances can be derived more accurately than absolute ones, and it is the relative heavy element abundance and not the absolute abundance that is important for determining relative distances. Furthermore, in some cases (such as the Pleiades) the required differences are large.

We have demonstrated that even modest departures from solar abundance can easily be measured by comparing distances inferred from metallicity sensitive and metallicity insensitive colors. We see no evidence for a subsolar Pleiades metal abundance.

Additional colors with different metallicity sensitivities would be useful to test the metallicity scale. For example, Robichon (these proceedings) inferred a larger difference in the metal abundances of the Pleiades and Praesepe from Geneva photometry than from BVI photometry. In this case, however, the distances derived from other color indices were not consistent for the adopted relative metal abundances. The inclusion of other color indices with well-calibrated metallicity sensitivities could be an important test of the robustness of photometric metallicities. In summary, changes in the metal abundances of clusters would significantly alter the distances, but there are several lines of evidence that argue against such a solution in the most problematic cases.

3.4. Color Transformations

An additional possibility is raised by Robichon (these proceedings): the absolute color calibrations may themselves be an error source. In addition, Robichon et al. (1999) pointed out that different investigators have obtained very different distances to the same open clusters. This indicates that at least in some cases the systematic errors in main sequence fitting have been underestimated.

Changes in the color-temperature relationship and bolometric corrections would manifest themselves as a shift in the zero-point of the cluster distance scale. This can be tested by comparing the isochrones with the Hyades distance; our method produces a Hyades distance in agreement with the Hipparcos distance for a solar-scaled helium abundance. Other transformations from the theoretical to the observational plane (e.g., Perryman et al. 1998) require a lower helium abundance for the Hyades to reproduce the distance inferred from other

methods. In our view this ends up substituting one problem (the Pleiades distance) for another (explaining the low inferred Hyades helium abundance.) In addition a systematic shift to lower distances would create tension between the Hipparcos and main sequence fitting distances to other clusters.

We agree with Robichon (these proceedings) that in some cases the systematic errors from main sequence fitting have been underestimated in previous studies. Different Hyades zero-point distances, neglecting cluster-to-cluster variations in metal abundance, deriving distances in only one color, and usage of the upper main sequence rather than the lower main sequence for distance estimates can all generate study-to-study scatter or even in some cases shifts in relative cluster distances. However, the precision of each of the individual studies must be examined to reliably infer their individual errors.

4. Possible Systematic Errors in the Hipparcos Parallaxes

Pinsonneault et al. (1998) analyzed the Hipparcos parallax data and found some evidence that suggested the systematic errors could be underestimated on small angular scales. Narayanan & Gould (1999ab) used a radial velocity gradient technique to infer the distances to the Hyades and Pleiades; in that study the deviations between the Hipparcos parallaxes and the stellar distances inferred from their method were found to exhibit spatial correlations. The idea that there are systematic errors in the Hipparcos parallaxes that cover large areas of the sky has been energetically challenged (see for instance Robichon et al. 1999.) More work needs to be done, especially involving other distance estimation techniques that can serve as independent tests of both main sequence fitting and systematic errors in the Hipparcos parallaxes at small angular scales.

5. Things to be Done

Quite aside from any connection to parallaxes, it is of value to extend the technique of main sequence fitting to more (and more distant) open clusters. The biggest need here is to obtain high quality multicolor photometry, from which the cluster metallicity and age (in certain age ranges) can be determined. Many potentially interesting clusters still have rather large distance errors because of incomplete membership or a lack of good estimates of the foreground extinction.

Finding better ages and distances bears upon many areas of research besides the obvious ones of calibrating standard candles (e.g., Cepheids) and of the evolution of the open cluster system. For example, some of the conclusions from open cluster studies such as lithium depletion depend on age and metallicity, not known well for many clusters.

Finally, we further that any new independent tests of errors in the Hipparcos parallaxes be performed.

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